Observation of Simultaneous Oscillation of Multiple Modes in a CW 300 GHz Gyrotron

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Multi mode oscillation was observed in a 300 GHz fully CW gyrotron. It has been developed and installed in Research Center for Development of Far-Infrared Region, University of Fukui as a power source of a submillimeter wave material processing system. This gyrotron delivers 1.75 kW / CW at maximum. The radiation pattern is a Gaussian beam when the magnetic field strength B_c at the cavity is properly adjusted. However, within a range of B_c, simultaneous oscillation of competing modes is observed, which manifests in radiation of the output power into multiple directions.

Keywords: Submillimeter CW gyrotron, Radiation pattern, Gaussian beam, Multi mode oscillation, Material processing

Medium power millimeter/submillimeter waves have a very wide field of application. One of promising applications is ceramic sintering and material processing. Recently, since a strong non thermal effect is expected for higher frequency power, use of 20 – 30 GHz gyrotrons is becoming popular [1]. However, CW gyrotron with a frequency of hundreds of GHz has not so far been realized as a power source for practical applications while a stronger non thermal effect can be expected. Thus realization of a gyrotron with this frequency range and kW order power is strongly desired.

Mode competition is a serious problem in the design and operation of a medium to high power, high frequency gyrotron because the mode density inevitably becomes very high owing to a highly over-sized cavity. Usually, a designated mode with the smallest starting current grows by suppressing competing modes and finally single mode oscillation is realized.

However, there is a chance of multi mode oscillation depending on the operation condition. We have observed this phenomenon on a fully CW 300 GHz gyrotron named as FU CW I. This is very interesting from the view point of the gyrotron physics. Moreover, understanding of the multi mode oscillation is a base for the development of medium power CW gyrotrons with further higher frequencies.

This gyrotron with a kW order output power has been developed according to the above requirement and installed in Research Center for Development of Far-Infrared Region, University of Fukui. It is the first gyrotron with these parameters for practical applications [2]. FU CW I works at the fundamental electron cyclotron resonance in a 12 T liquid helium free superconducting magnet. It is operated at a rather low cathode voltage of 15 kV. The maximum beam current is 1 A.

The designated cavity mode of FU CW I is $TE_{22,8}$. The radius of the flat region of the cavity R_c is 8.39 mm and the resonance frequency of the $TE_{22,8}$ mode is almost 300 GHz. The length of the flat region of the cavity is 15 mm and the total Q value including the Ohmic loss is about 6000 [3]. A mode converter composed of a radiator of Vlasov type and three beam shaping mirrors is equipped inside the gyrotron. The output power is delivered through the vacuum window in a Gaussian beam. The vacuum window is made of BN and its diameter is 80 mm. This gyrotron can be operated either in CW mode or in pulse mode.

Performance test of FU CW I has been carried out in advance of the commissioning in the material processing system. The maximum CW output power of 1.75 kW has been attained. This power was measured with a water load at just outside of the vacuum window. The radiation pattern was measured with an infrared camera. A Gaussian beam with a very low level of the side lobe was confirmed when the magnetic field strength B_c at the cavity was properly adjusted. The oscillation was identified as the designated $TE_{22,8}$ mode from frequency measurement with a combination of a harmonic mixer and a local oscillator [4].

Mode competition was observed in a range of the parameter space of B_c and the cathode voltage V_c. Several modes oscillated simultaneously. This manifested in radiation of the output power into multi directions. Then the radiation pattern was measured in detail. The radiation pattern appears as a profile of temperature rise on an absorber made of 1 mm thick polyvinyl chloride plate.

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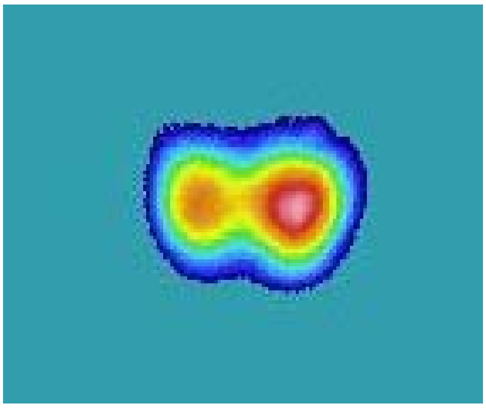

Fig. 1 An example of the infrared camera image for V_c = 15 kV and B_c = 10.90 T. The distance between the two peaks is about 3 cm.

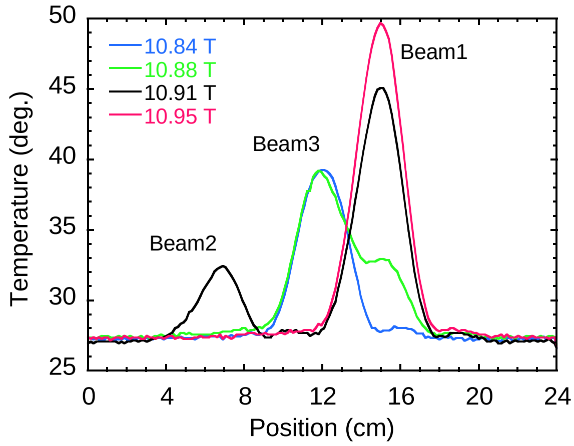

Fig. 2 Temperature distributions along the horizontal line that passes the peak temperature position.

Figure 1 represents a typical temperature profile for a case of two peaks. For this case, V_c was 15 kV and the beam current I_b was about 1 A. The multi peak radiation pattern sensitively depends on B_c and V_c. For $V_c \leq 12$ kV, a single peak radiation is observed within almost all range of B_c.

The multi peak character also depends on B_c. Figure 2 shows the temperature distribution of the absorber along the horizontal direction for different B_c with V_c being fixed at 15 kV. Multi peaks always appear along the horizontal direction and the position corresponding to each peak does not vary for different B_c. Therefore, each peak is considered to correspond to different oscillation mode. As shown by the red line in Fig. 2, only one beam is radiated when B_c is set at 10.95 T. This beam is radiated to the same direction as that for V_c of 12 kV, at which only one beam is radiated in a wide range of B_c. This oscillation was identified to be the $TE_{22,8}$ mode from the frequency measurement. Thus, the radiation shown by the red line in Fig. 2 originates from the $TE_{22,8}$ mode. We refer to this beam as Beam 1.

The peak temperature of the absorber corresponding to the power of Beam 1 decreased with decreasing B_c. A new peak appeared in the position left to the peak of Beam 1 when B_c was slightly decreased as depicted by the black line in Fig. 2. We call this beam as Beam 2. The output power of the oscillation corresponding to this peak was rather low and disappeared for smaller B_c. Instead, another peak turned up in between Beam 1 and Beam 2. The green line in Fig. 2 stands for this case. This peak is referred as Beam 3. When B_c is further decreased, Beam 1 disappeared and Beam 3 alone was observed as shown by the blue line in Fig. 2. The difference of B_c between the case of the red line and the case of the blue line is 0.11 T.

In addition to the $TE_{22,8}$ mode, $TE_{19,9}$ mode was also identified from the frequency measurement. The difference of 0.11 T in B_c just corresponds to that between the optimum values of B_c for both modes. Therefore, Beam 3 is considered to originate from the $TE_{19,9}$ mode. The counter-rotating $TE_{19,9}$ mode is the most dangerous competing mode. The oscillation mode corresponding to Beam 2 has not been identified yet.

The $TE_{22,8}$ mode and the $TE_{19,9}$ mode simultaneously oscillate in a range of B_c when V_c is larger than 13 kV. When the beam current I_b is decreased, the oscillation range of B_c becomes slightly narrower for each mode. Finally, the multi oscillation region disappears for I_b smaller than 0.3 A.

The radiation pattern has been measured in the pulse mode to avoid burn up of the absorber but the infrared camera records the temperature profile on the absorber plate as a result of time integration of the absorbed power. Therefore, the multi peak pattern does not directly means simultaneous oscillation of multi modes. Then, pyroelectric detectors were set on the lines of Beam 1 and 3. The signals of the two detectors clearly showed simultaneous and full time oscillation of the two modes during the cathode voltage pulse. For each beam, the dependence of the signal intensity on B_c is similar to that of the temperature rise on B_c.

Simultaneous oscillation of multi modes was observed in 140 GHz gyrotron [5]. The main operation mode of this gyrotron was rather low mode TE_{03} at the fundamental resonance. Competition between the fundamental and the second harmonic oscillations was also reported [6]. The frequency of the second harmonic oscillation was 383 GHz. Compared with these experiments, the oscillation modes of FU CW I are very high.

Another problem is how the counter-rotating mode can be radiated as a Gaussian beam through the internal mode converter of Vlasov type. The co-rotating $TE_{19,9}$ mode could be excited but its optimum radius of the electron beam is considerably smaller than that of the counter-rotating $TE_{19,9}$ mode. We have not come to physical understanding yet. Results of more detailed analysis of experimental data and theoretical discussion will be published elsewhere.

[1] H. Hoshizuki et al., Int. J. Infrared and Millimeter Waves, **26**, 1531 (2005).

[2] S. Mitsudo et al., *Conf. Digest of 31th IRMMW & 14th THz* (2006) p.572.

[3] V. E. Zapevalov et al., *Conf. Digest of 29th IRMMW & 12th THz* (2004) p.149.

[4] T. Saito et al., *Conf. Digest of 31th IRMMW & 14th THz* (2006) p.24

[5] K. E. Kreischer et al., IEEE Trans. Microwave Theory and Tech. **MT-32**, 481 (1984).

[6] T. Idehara et al., Phys. Fluids B **4**, 267 (1992).